Newsletter
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XtremeHeatAUS - Modelling Heatwave Deaths

Introduction

Heatwave hazard modelling

Research undertaken by Risk Frontiers shows that since 1900, with the exclusion of disease epidemics, heatwaves have been responsible for more deaths in Australia than *all other natural hazards put together.* In particular the South East Australia Region has been affected by 6 of the top 10 most deadly Australian events since the beginning of the 20th century (Coates et al. 2014).

Despite this death toll there is as yet no consensus about what constitutes a heatwave event or even about how one should go about quantifying their intensity. Acknowledging this gap Nairn and Fawcett (2015) designed a heatwave index that takes into account: (i) the ability of the local community to adapt to its climate and (ii) the impact of sharp temperature spikes that do not allow such acclimatisation. This Excess Heat Factor (EHF) is briefly described separately at the close of this article. We have adopted it here to homogenise the description of heatwave hazard intensity across the country.

A key question driving the development of XtremeHeatAUS is if knowing the peak EHF intensity ($\mathrm{EHF}_{\mathrm{max}}$) and its accumulated sum over the lifetime of an event ($\mathrm{EHF}_{\mathrm{sum}}$), can we anticipate the impact of that event on human lives? The second focus is to assess the risk in a given region, or nationally, of heatwave deaths in much the same way as our other models do for property damage caused by other natural perils: in other words, what is the average annual death rate from heatwaves and what would be the death toll in a 1-in-100 or 1-in-250 year event.

In what follows we discuss the development of a physically realistic set of events representative of 1000 years of heatwave activity in Victoria / South Australia and which allow detailed analysis of the associated risk to human life in that region. We then extrapolate that risk nationally using PerilAUS data.

Heatwave hazard modelling

Risk Frontiers' heatwave death model, XtremeHeatAUS, shares the same conceptual philosophy of risk that lies behind other NAT CAT models in terms of hazard characterisation, exposure and vulnerability. In terms of characterising the hazard, we adopt the Excess Heat Factor as a means

Risk Frontiers Annual Seminar: A Provisional Programme

Wednesday 26th October, 2016, commencing 2.00pm
at the Museum of Sydney, cnr Phillip & Bridge Streets, Sydney

Apart from the customary drinks and nibbles, this year there is even more on the menu.

Silent Witness meets reality: lessons from the December 2015 Wye River fires.

This year's guest speaker, Justin Leonard, is an engineer who leads CSIRO's Bushfire Urban Design team and regularly undertakes forensic examinations of destroyed buildings following bushfires. He will take you through the bushfire pathology of buildings and of this particular event in particular.

Yeah! At last! A truly national hail loss model.

Christina Magill will discuss our latest release of HailAUS employing an updated climatology, reanalysis data, radar information and other bells and whistles. Amazing!

Surviving bushfires.

Katharine Haynes will talk about conclusions emerging from her study of survivor accounts and the coronial reports of victims on sheltering from bushfires during the 2009 Black Saturday fires. Salutary.

QuakeNZ – what would be cost today of a repeat of the 1931 Napier event or the impact on Wellington of a repeat of the 1855 Wairarapa earthquake?

Hear this and more as Valentina Koschatsky introduces the key features of our new NZ earthquake model -- the first post-Christchurch. What can you say?

OCT
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please note this date in your diary

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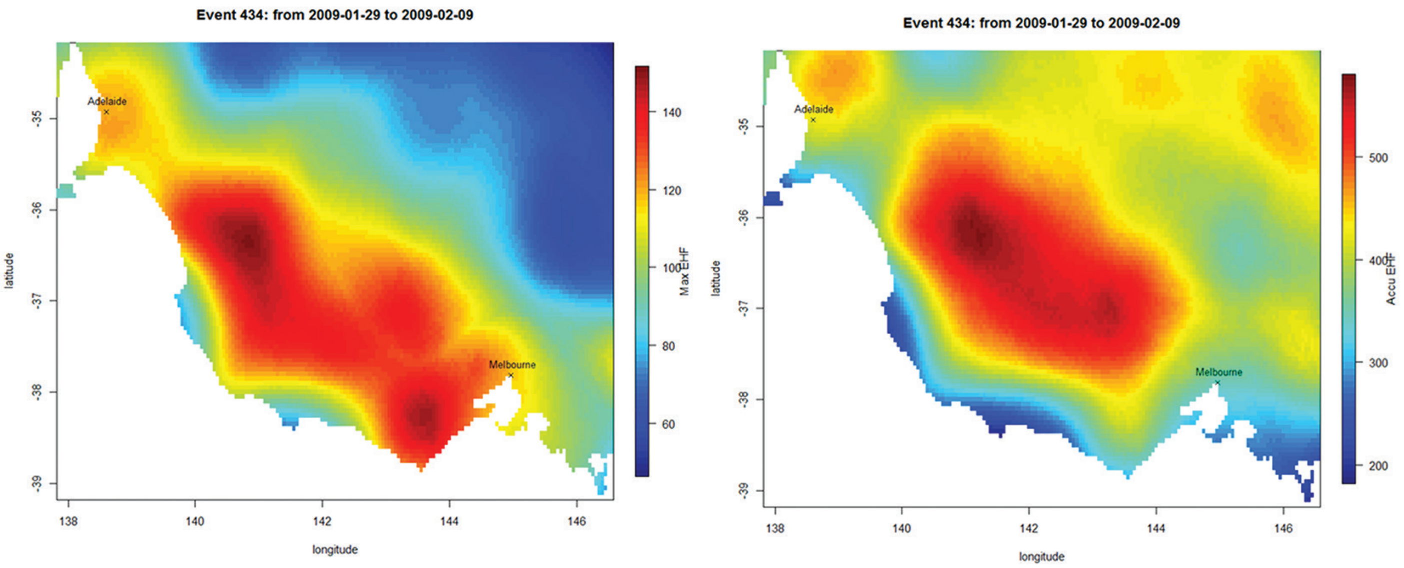

Figure 1: Footprint of peak EHF (EHF_{max}, left) and accumulated EHF (EHF_{sum}, right) for the January-February 2009 event.

to quantify the spatial distribution of heatwave intensity and use the past 100 years of gridded daily minimum and maximum temperature records available from the Australian Bureau of Meteorology (hereafter referred to as the BoM dataset) to compute EHF estimates over a geographical domain that extends from Adelaide to Melbourne (Figure 1).

Any occurrence of three consecutive days with positive EHF in a given 5 km by 5 km grid cell was considered to trigger a heatwave event. There are other ways to define the onset of a heat event but this 3-day period is used here to limit the number of events in our dataset.

Once triggered, an event lasts until no cell in the domain is left with a positive EHF. A total of 466 events were identified that satisfied this criterion, and for each, the gridded peak and accumulated EHF values were recorded over the lifetime of each event: an example of the hazard footprint is provided in Figure 1. The left-hand figure shows the spatial distribution of the peak EHF value of the January – February 2009 event that killed more people that the Black Saturday bushfires that took place during that same period. The right-hand figure shows the accumulated EHF over the same time period.

However even a hundred years of history will not have explored the full range of possible heatwave events and so with the aim of extrapolating the data from this catalogue beyond what has been experienced in the past century, a detailed analysis of the key components of heatwave footprints in the region was undertaken. For this purpose the 466 peak and accumulated EHF footprints since 1911 were decomposed using a Principal Component Analysis (PCA) approach.

PCA is a statistical procedure that uses an orthogonal transformation to convert a set of observations of possibly correlated variables into a set of values of linearly uncorrelated variables called principal components. This family of vectors called empirical orthogonal functions (EOFs) allow decomposition of the field of interest using a set of event specific coordinates.

With the EOFs ordered in terms of importance according to the percentage of the variance explained, this decomposition enables analysis of the key patterns of variability. This reconstruction can easily be truncated to keep only the leading vectors, providing a practical and computationally efficient means of generating synthetic events consistent with the observed historical variability. (In other work at Risk Frontiers, we are using a similar approach to construct more realistic Tropical Cyclone windfields than the parametric equations normally used in NAT CAT modelling.)

Defining new hazard intensity categories for heat-related fatalities

Having identified objective measures to quantify heatwave footprints and developed a method to produce realistic synthetic events, we now investigate their link to heat-related fatalities by analysis of two data products.

First, the PerilAUS archive (Coates et al. 2014) records 224 historical occurrences of events with heat-related deaths in Australia since 1900 with the number of fatalities reported, along with their dates and location (lat. long.).

Secondly, we exploit the past 100 years of records of daily minimum and maximum temperature from the BoM dataset and compute EHF estimates for the 12 days prior to the reported date of death. This 12-day period is long enough to cover most event durations.

From a ranking of major heatwave episodes, each associated with significant deaths, in terms of the accumulated EHF and peak intensity, we define five new heatwave severity categories. These categories capture conditions that historically led to a higher number of deaths.

The combined classification scheme employs the union of both the maximum EHF and its accumulated sum over the event ($EHF_{max} > x \cap EHF_{sum} > y$) as defined in Table 1. While one could design a categorisation of events based on either one of these indicators, we chose to combine both metrics acknowledging that most severe events will be characterised by both a large

Table 1: Criteria for the classification of heatwave events. Both criteria (columns 2 and 3) must be satisfied.

CATEGORY	EHF_{SUM}	EHF_{MAX}
CAT0	> 0	> 0
CAT1	> 30	> 15
CAT2	> 80	> 30
CAT3	> 150	> 50
CAT4	> 300	> 70
CAT5	>450	>100

peak maximum (EHF_{max}) and a sustained period of high EHF (EHF_{sum}).

To illustrate how the classification in Table 1 can be used to characterise specific events, we return to the 2009 event using the footprints of EHF_{max} and EHF_{sum} displayed in Figure 1 and create the spatial pattern of categories following the schema given in Table 1. The resulting category map along with records of fatalities (black dots) in shown in Figure 2. Unlike continuous maps of EHF_{max} or EHF_{sum} values, these allow direct representation of the risk gradient across the event footprint.

Developing an EHF-based vulnerability function to project fatalities

In order to estimate heat-related fatalities based on both peak and accumulated EHF values during a heatwave event, a vulnerability function is derived using census population data from between 2001 and 2011 to normalise the fatality records. The vulnerability development is restricted to that period and the focus is again on the Victoria / South Australia region.For the 10 biggest events of the period the total population exposed to each of the categories listed in Table 1 is computed, linearly interpolating between records from 2001 and 2011. The corresponding fatalities reported in that same exposed area are then totalled and normalised by the exposed population in order to derive a death rate by category. Figure 3 shows the expected number of fatalities per 100,000 people exposed for each category.

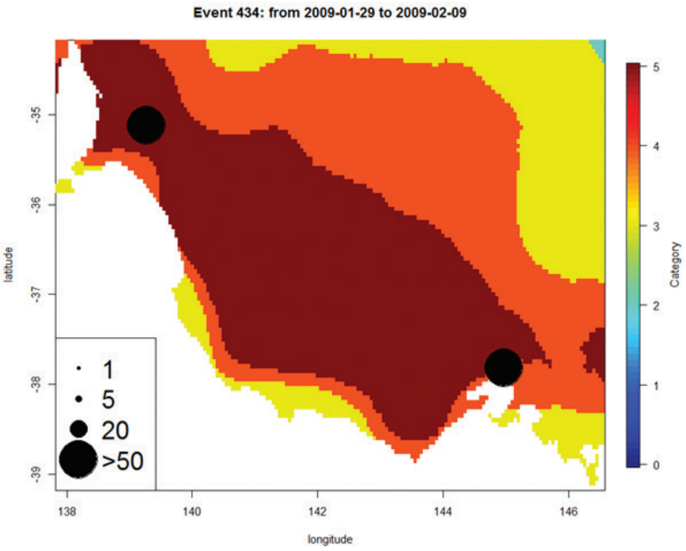

Figure 2: Map of Table 1 heatwave severity categories for the January-February 2009 event. The dots represent Melbourne and Adelaide

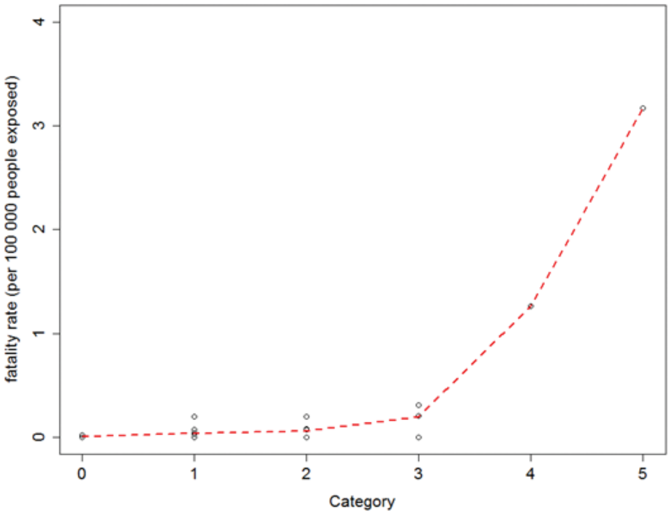

Figure 3: Rate of fatalities per 100 000 people (y-axis) as a function of the heatwave category they are exposed to (x-axis). Individual dots represent distinct events while the red dashed line is the expected estimate, representative of all-events combined.

Modelling flow and key results

The model components above were combined to simulate 1000-years of heatwave activity in the domain covered by Figure 1. The iterative process in which the fatality count from each event is simulated is described below:

- For every year in the 1000-year period, the number of events occurring is sampled from the distribution of historical event annual frequencies as observed over the past century.
- For every event, footprints of both the peak and accumulated EHF values are simulated, event footprints reconstructed and the new category scheme applied. In this way a map of heatwave risk similar to Figure 2 is created for each simulated event.
- Using the vulnerability curve along with an estimate of the population in each of the 5 km grid cells covering the domain of study, the mean expected number of fatalities per cell is computed.
- The total number of fatalities is then summed for each event and by year to estimate the probability of exceedance of given death thresholds.

In this way, Risk Frontiers has produced a catalogue of synthetic events representative of 1000-years of heatwave activity in Victoria and South Australia. Figure 4 shows an example of the 100-year return period risk footprint for the region. The risk is highest around Adelaide and inland due to higher heat accumulation.

The annual average death toll is estimated at 19 for the region and that associated with a 1-in-10 year event, for example, is estimated at 33. 192 deaths are expected from a 1-in-100 year event in the region, a figure that has been exceeded twice in our historical records (1908 and 2009). Only one event in the

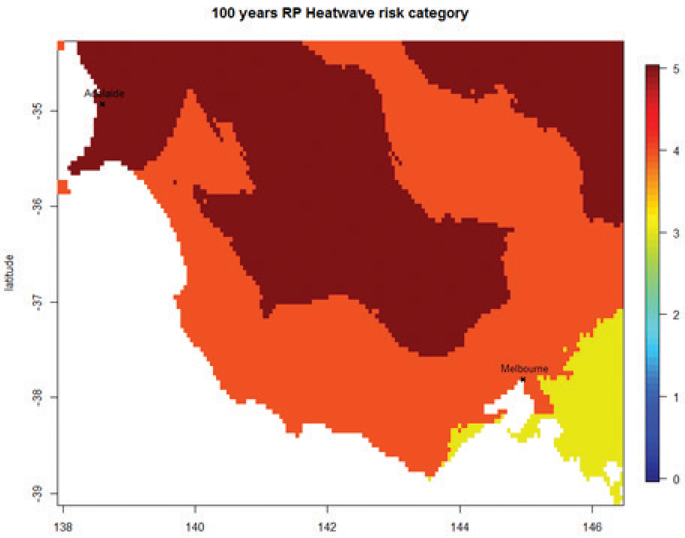

Figure 4: 100-year return period risk in terms of heatwave categories

1000 years simulated reaches the same range of fatalities observed during the January-February 2009 event suggesting this was a very rare occurrence for the region.

Extrapolation to the rest of the country

In order to extrapolate our findings nationally, we could model the entire country in the same way as described above for the Adelaide/Melbourne region. For our purposes here, however, we simply extrapolate using the PerilAUS results (Coates et al. 2014) as an indication of the relative risk in each Australian state. Table 2 below summarises the values applied to scale up the annual average fatality from Victoria/South Australia to the rest of the country.

The projected average annual number of fatalities for the country as a whole is 33. While this number may not seem large, it lies between the 14 normalised deaths reported by Crompton et al. (2010) for bushfire fatalities and the ~100 deaths that occur annually in structural house fires. Given the national investment in responding to the fire threats, one might expect a similar concern about heatwaves.

Table 2: Historical fatality records and projected annual average estimates for each region and the country as a whole.

REGION	HISTORICAL FATALITIES	RATIO OF VIC/SA	PROJECTED ANNUAL AVERAGE
VICTORIA/SOUTH AUSTRALIA	1148	1	18.4
NEW SOUTH WALES	580	0.505	9.3
QUEENSLAND	180	0.157	2.9
WESTERN AUSTRALIA	107	0.093	1.7
NORTHERN TERRITORY	26	0.023	0.4
TOTAL	2041	1.778	32.7

In contemplating these numbers it is important to recognise a couple of factors:

1. All estimates in this study have been based on reported fatalities, and because of under-reporting and the likelihood of wrongly categorising deaths to other health-related issues rather than heat stress, our projections should be interpreted as lower bound estimates.
2. As with other natural hazards, the average annual numbers of fatalities is a poor estimate of the magnitude of the threat because of the long-tailed distribution of possible outcomes. As we saw in the 2009 event with an estimated death toll of 432 lives, much greater losses are possible in individual years. This is also true of bushfire deaths.

Lastly we note that PriceWaterhouseCoopers have also considered heatwave deaths with a focus on how climate change might amplify the death toll. They determined 80 excess deaths on average across Australian capital cities, a number roughly double our estimate. However, there is insufficient knowledge about the assumptions employed in that study for their calculations to be replicated.

For further information and the bibliography please contact:
Dr Thomas Loridan (Thomas.Loridan@mq.edu.au).

The Excess Heat Factor

Although there exist many ways to define a heatwave event, the Excess Heat Factor methodology introduced by Nairn and Fawcett (2015) is being adopted as the standard metric in Australia. It recognises the need to account for both minimum and maximum daily temperatures when assessing heatwave intensity and explicitly separates the impact of short- and long-term temperature anomalies.

Firstly, an excess heat index is computed to capture atypical occurrences of higher heat accumulation at a particular location in respect to its long-term average. For this purpose the daily mean temperature (TM) calculated as the average of the night time minimum and daytime maximum air temperatures are averaged over a three-day period and compared to the 95th percentile of TM at the location of interest (TM95). Daily minimum and maximum temperature data for Australia are available from the Bureau of Meteorology from the start of the 20th century.

The *significant* excess heat index on day i is defined as follows:

$$EHI_{SIG}(i) = max\left[\frac{(T_{Mi}+T_{Mi-1}+T_{Mi-2})}{3} - T_{M95}, 0\right] \qquad (1)$$

A positive EHI_{SIG} indicates an unusually warm three-day period relative to the local climate statistics while all other days are assigned a value of zero.

Secondly, an acclimatisation index (EHI_{ACC}) is bought into play to capture sudden rises in temperature in relation to the recent past. The index is computed in a similar fashion to Equation (1), this time comparing the three-day average to the past month (30-day) average:

$$EHI_{ACC}(i) = \frac{(T_{Mi}+T_{Mi-1}+T_{Mi-2})}{3} - \frac{\sum_{k=3}^{33} T_{M(i-k)}}{30} \qquad (2)$$

Here a positive value of EHI_{ACC} indicates a sharp temperature rise, to which the local population might not have had time to acclimatise.

Thirdly, the Excess Heat Factor (EHF) is obtained as a combination of EHI_{SIG} and EHI_{ACC}:

$$EHF(i) = EHI_{SIG}(i) \times max\big(1, EHI_{ACC}(i)\big) \qquad (3)$$

Any given day is considered in a heatwave if the EHF has been positive for at least three consecutive days (a single positive EHF value does not define a heatwave). Consequently the occurrence of a heatwave is conditional on EHI_{SIG} being positive for at least 3 consecutive days while the influence of EHI_{ACC} is to amplify the magnitude of the EHF estimate and reflect unusual short-term warming.

The strengths of the EHF as a measure of heatwave occurrence and intensity are that it is (i) location dependent, and explicitly acknowledges that populations in warmer climates are more resilient in the face of higher daily mean temperatures and (ii) accounts for both short term and climate scale temperature anomalies.

Finally, the EHF can be extended as an accumulated index to better characterise changing heat load over time. For that purpose the daily EHF values are summed over a certain time period, such as the lifetime of a heatwave event. The resulting integrated value represents the overall intensity of the event accounting for both the event duration and its strength over time.

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